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Frictional behavior of bearing material under gas lubricated conditions

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Abstract

In this study, a Taguchi method is employed to determine statistically the optimal design parameters, and investigate the effect of gas lubrication on friction behavior of bearing material, which is carbon chromium steel. By selecting L_9 Taguchi's orthogonal arrays, nine sliding tests were carried out in air, O_2- and N_2-gas lubrication in accordance with the ASTM standard G99-95a. The test was performed over a broad range of applied loads (*W*), sliding velocities (*v*) and sliding distances (*L*) using a ball-on-disc tribometer. At higher applied load, sliding speed and sliding distance, it was found that gas blown to the sliding surfaces in air effectively reduced the coefficient of friction as compared to the air lubrication. In addition, based upon the mean of signal-to-noise (*SN*) ratio analysis, the sliding speed is the most influencing factor for minimizing coefficient of friction. In this study, the optimal design parameters for a lower coefficient of friction (μ) are: lubricant = N_2, W = 10N, v = 1000rpm, L = 1km. By using the optimal design parameters, a confirmation test successfully verified that the N_2-gas lubrication reduced coefficient of friction by 24%. This is in accordance with a significant reduction of wear scar diameter and smoother worn surface on the ball.

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Keywords: Gas lubrication; Carbon chromium steel; Coefficient of friction.

Nomenclature

F	frictional force (N)
W	applied load (N)
H	hardness (HRC)
R_a	surface roughness
SN	signal-to-noise
DoE	design of experiment
v	sliding speed (rpm)
L	sliding distance (km)

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Greek symbols

μ coefficient of friction

ρ density (g/cm^3)

1. Introduction

Gas lubrication has several advantages, such as high precision, small friction loss, non–polluting, long life and attractive for high-temperature applications [1]. Meanwhile, gas-lubricated bearing is virtually frictionless, silent, and vibration-free. Gas bearings can be used for extremely large surface velocities. A gas bearing can eliminate the risk of contaminating a process with lubricant.

Cong et al. [2] found that HFC-134a gas significantly reduces the friction and wear of all the ceramic couples (ionic ceramics Al_2O_3 and ZrO_2, and the covalent ceramics Si_3N_4 and SiC rubbing against an Al_2O_3 ball), and that the ionic ceramic pairs show lower friction and wear. Oxygen has been found to lubricate SiC by the formation of silica and the release of graphite-like material [3], while benzene and acetone vapors have been found to form sticky reaction products, which reduce the friction and wear of ZrO_2 [4].

From the past studies, the friction of materials is effectively reduced by different gas lubrication. Thus, in this study, the friction behavior of bearing material, which is carbon-chrome steel, sliding in air with O_2- or N_2-gas blows are investigated using a systematic approach, which is Taguchi method. The optimal design parameters and the most significance parameter are obtained by employing analysis of signal-to-noise (*SN*) ratio.

2. Experimental procedures

2.1. Design of Experiment (*DoE*)

Prior to experimental work, *DoE* using Taguchi method was employed. Four design parameters were determined (lubricant, applied load, sliding speed and sliding distance) and three levels were taken for each parameter, as shown in Table 1. In this study, the L_9 (3^4) orthogonal arrays was selected using Minitab statistical software, as shown in Table 2.

Table 1. Design parameters at three different levels

Level	Design parameters			
	Lubricant	Applied load (*W*), N	Sliding speed (*v*), rpm	Sliding distance (*L*), km
1	Air	5	50	1
2	N_2-gas	10	1000	3
3	O_2-gas	20	1500	5

Table 2. Taguchi L_9 (3^4) orthogonal arrays

Test	Design parameters			
	Lubricant	Applied load (*W*), N	Sliding speed (*v*), rpm	Sliding distance (*L*), km
1	Air	5	500	1
2	Air	10	1000	3
3	Air	20	1500	5
4	N_2-gas	5	500	5
5	N_2-gas	10	1000	1
6	N_2-gas	20	1500	3
7	O_2-gas	5	500	3
8	O_2-gas	10	1000	5
9	O_2-gas	20	1500	1

2.2. Materials

The materials used in this study were carbon-chrome steel (SKF bearing) for a ball and EN-31 for a disc. The ball has an average surface roughness (R_a) of 0.023μm. The mechanical properties of materials are shown in Table 3.

Table 3. Mechanical properties of materials

Properties	Carbon chromium steel[1]	EN-31[2]
Hardness (*H*), HRC	61	62
Density (ρ), g/cm^3	7.79	7.81

[1]From laboratory measurements.
[2]From manufacturer.

2.3. Tribological testing

By selecting L_9 Taguchi's orthogonal arrays as in Table 2, nine sliding tests were carried out using a ball-on-disc tribometer in accordance with ASTM standard G99-95a [5], as illustrated in Fig. 1. Each test was repeated two times in order to reduce experimental errors. Gas was blown to the sliding surfaces in air at a constant pressure of 10psi (70kPa), as shown in Fig. 2. All tests were performed at room temperature. Prior to the sliding test, both ball and disc were cleaned using acetone in an ultrasonic bath. The ball and disc has a diameter of 11mm and 165mm (thickness of 8mm), respectively.

The frictional force encounters by the ball in sliding were measured by a PC based data logging system. The coefficient of friction (μ) is then being determined as follows:

$$\mu = F/W \tag{1}$$

Where F is the frictional force in N and W is the applied load in N.

Statistical analysis using Taguchi method was then employed to determine the optimal design parameters and investigate the effect of gas lubrication on friction behavior of carbon-chrome steel. Then, a confirmation test was carried out to verify the improvement of the quality characteristic using optimal levels of the design parameters.

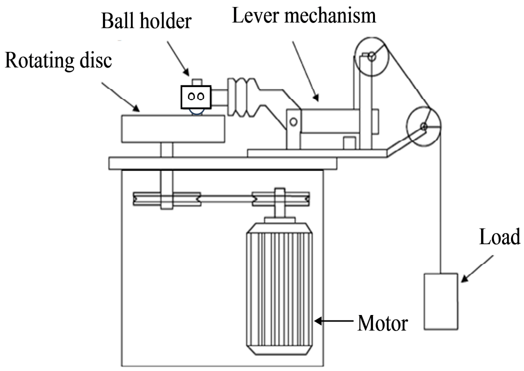

Fig. 1. Schematic diagram of a ball-on-disc tribometer.

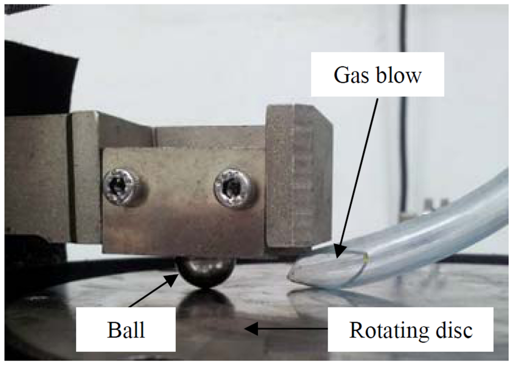

Fig. 2. Photograph of gas blown to the sliding surfaces.

3. Results and discussion

3.1 Effect of gas lubrication on friction behavior of bearing material

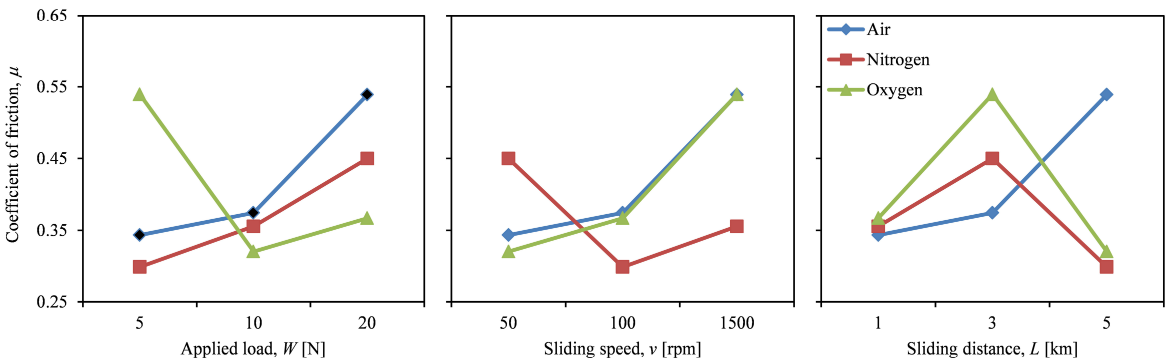

Fig. 3. Interaction plot for coefficient of friction.

Generally, two surfaces of adjacent moving parts can be seperated by a thin film to minimize direct contact between them and provides an interface of low shear strength, hence reduce friction and wear. In this study, the presence of gas lubrication potentially created a thin film and lowered the coefficient of friction at higher applied load, sliding speed and sliding distance as compared with the air lubrication, as shown in Fig. 3. This may be due to the shear strength increases less in proportion to the applied load, sliding speed and sliding distance; this leads to a slight reduction of friction.

3.2 Optimal design parameters

In order to quantify the optimal value to each design parameter, mean of *SN* ratio for coefficent of friction was computed, as presented in Fig. 4. A greater *SN* ratio value corresponds to a better performance (low coefficient of friction). A small increase as a mean of *SN* ratio indicating that the presence of N_2-gas lubrication effectively reduced coefficient of friction. Additionally, based upon the rank of mean of *SN* ratio as shown in Table 4, the sliding speed is the most influencing factors for minimizing coefficient of friction. In this study, the optimal design parameters for a lower coefficient of friction are identified as follows: lubricant = N_2, W = 10N, v = 1000rpm, L = 1km.

A comparison between the optimized values in air and N_2-gas lubrication is shown in Fig. 5. A confirmation test can successfully verify the N_2-gas lubrication reduced coefficient of friction by 24% (Fig.5(a)). This is in accordance with a significant reduction of wear scar diameter (Fig. 5(b)). Furthermore, Fig. 6 shows that a smoother worn surface (R_a = 0.162µm) was also obtained under N_2-gas lubricated conditions.

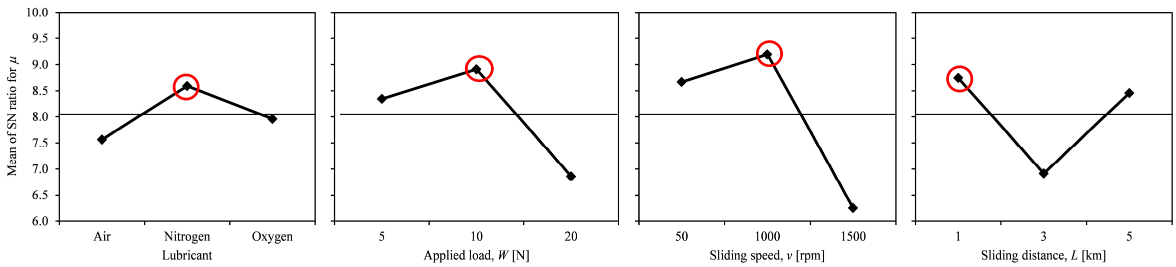

Fig. 4. Mean of *SN* ratio for coefficient of friction. The optimal design parameters are shown by a red circle.

Table 4. Response table of *SN* ratios for coefficient of friction

Test	Design parameters			
	Lubricant	Applied load (F), N	Sliding speed (v), rpm	Sliding distance (l), km
1	7.564	8.345	8.667	8.745
2	8.591	8.911	9.193	6.914
3	7.959	6.859	6.254	8.456
Delta	1.027	2.052	2.939	1.831
Rank	4	2	1	3

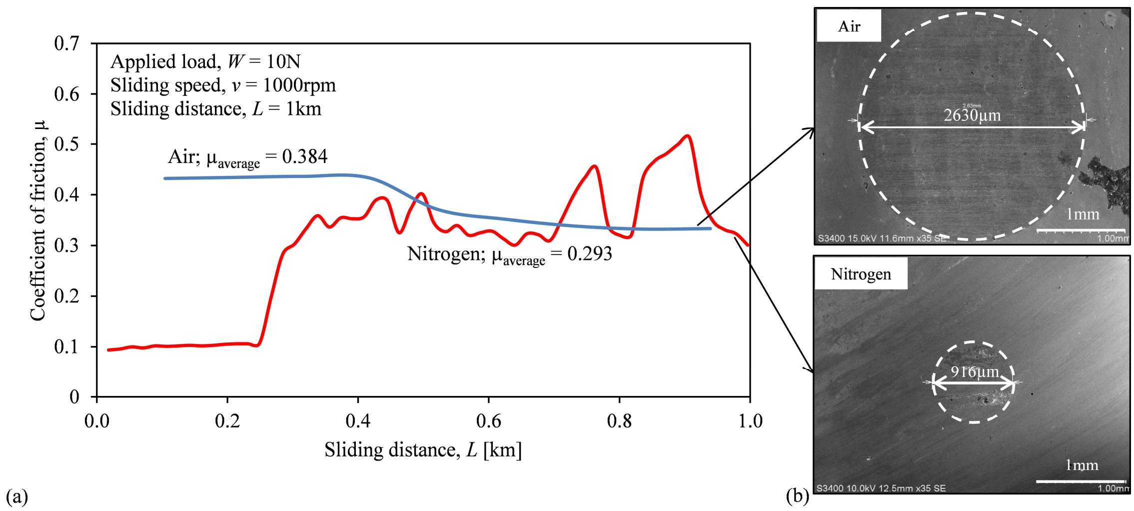

Fig. 5. A confirmation test results by comparing (a) the coefficient of friction and (b) Scanning Electron Microscopy (SEM) of worn surfaces on a ball under air and N_2-gas lubricated conditions using optimal design parameters.

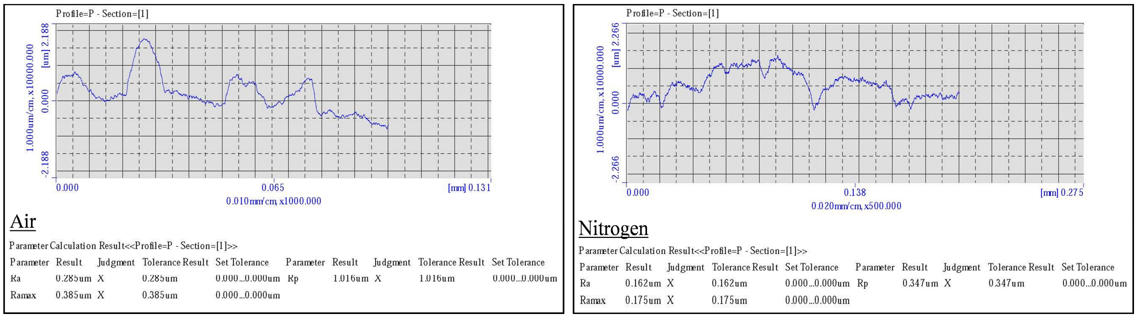

Fig. 6. Surface profile of worn surfaces on a ball under air and N_2-gas lubricated conditions using optimal design parameteres.

4. Conclusions

The following conclusions may be drawn from the present study:

1. As compared to the air lubrication, the presence of gas lubrication lowered the coefficient of friction at higher normal load, sliding speed and sliding distance. This may be due to the shear strength increases less in proportion to the applied load, sliding speed and sliding distance.
2. Based on mean of *SN* ratio analysis, improvement of friction reduction primarily depends on the sliding speed.
3. The optimal design parameters for a lower coefficient of friction (μ) are: lubricant = N_2, W = 10N, v = 1000rpm, L = 1km.
4. By using the optimal design parameters, a confirmation test successfully verified that the N_2-gas lubrication reduced coefficient of friction by 24%. This is in accordance with a significant reduction of wear scar diameter and smoother worn surface on the ball.

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